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a numerical and experimental study of capture efficiency

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Publication date:
1993

Document Version
Publisher's PDF, also known as Version of record

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LOCAL EXHAUST VENTILATION - A NUMERICAL AND EXPERIMENTAL STUDY OF CAPTURE EFFICIENCY

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ABSTRACT

Capture efficiency of a local exhaust system, e.g. a kitchen hood, should include only contaminants being direct captured. In this study basic concepts of local exhaust capture efficiency are given, based on the idea of a control box. A validated numerical model is used for estimation of the capture efficiency. An experimental technique is introduced for field studies taking into account knowledge of flow patterns of air and contaminants obtained from smoke testing and contaminant concentrations. Holding together numerical and experimental data a fair agreement is observed.

INTRODUCTION

The main function of a kitchen hood is to extract pollution from cooking in order to keep the pollution level in the occupied space as low as possible. Basically a kitchen hood is intended to provide an air movement that will carry pollutants from the domain of release into the exhaust opening. It is common practice to characterize pollutant removal performance of kitchen hoods in terms of capture efficiency defined as the ratio between the flow rate of captured pollutants and the total emission rate of pollutants from the source. Although fairly simple in principle it is far from obvious how to estimate capture efficiency of a local exhaust system, e.g. a kitchen hood. As discussed elsewhere (1) standards for testing of kitchen hood capture efficiency are available. The purpose of this study is to introduce some fundamental concepts of local exhaust capture efficiency, and to derive general recommendations for testing of local exhaust systems. The study is not aimed at kitchen hoods but at local exhaust ventilation in general.

METHODS

Concepts of local exhaust capture efficiency

Consider a local exhaust opening (flow rate q_{le}) at a source of constant emission rate, S. At steady state the capture rate of the exhaust is S_{le} and concentration at the exhaust duct is C_{le}. Then the total capture efficiency is

$$\eta_{le}^{tot} = \frac{S_{le}}{S} = \frac{q_{le} \times c_{le}}{S} \qquad (1)$$

As pointed out by Jansson (2) S_{le} should include only contaminants being direct captured. Let this "direct" efficiency be denoted η^{d}_{le}. An estimate of η^{d}_{le} can be obtained from a mass balance of a control box containing the source and the exhaust opening. By definition pollutants kept within the control box are considered to be direct captured (Figure 1).

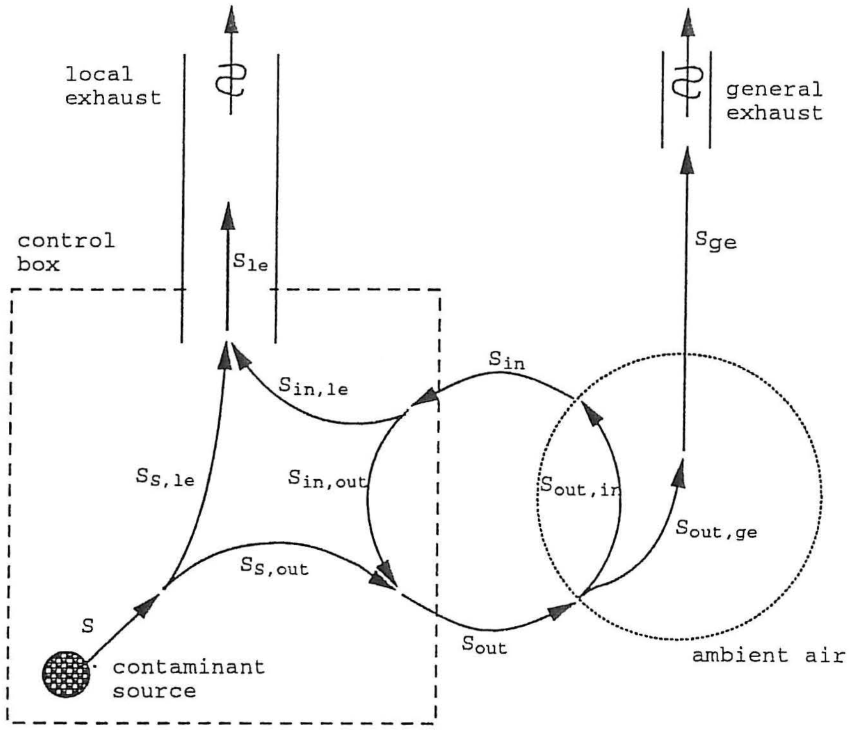

Figure 1. Control box to distinguish between direct captured and escaped contaminants.

Part of the generated contaminant S is captured direct by the local exhaust, $S_{S,le}$, and the remaining part, $S_{S,out}$, escapes the control box. Part of the escaped contaminants returns into the control box, $S_{out,in}$, and the rest is captured by the general exhaust, $S_{out,ge}$. Part of $S_{out,in}$ is captured by the local exhaust, $S_{in,le}$, and the rest escapes the control box, $S_{in,out}$. With a reference to Figure 1 the following mass balance applies to the control box

$$S + S_{in} = S_{le} + S_{out} \tag{2a}$$

where
$$S = S_{S,le} + S_{S,out} \tag{2b}$$

$$S_{in} = S_{in,le} + S_{in,out} = S_{out,in} \tag{2c}$$

$$S_{le} = S_{in,le} + S_{S,le} \tag{2d}$$

$$S_{out} = S_{out,ge} + S_{out,in} = S_{S,out} + S_{in,out} \tag{2e}$$

By definition the direct capture efficiency, η^d_{le}, is derived from

$$\eta^d_{le} = \frac{S_{S,le}}{S} = \frac{S_{le} - S_{in,le}}{S} = \eta^{tot}_{le} - \frac{S_{in,le}}{S} \tag{3}$$

Emission rate is considered to be known, and S_{le} is obtained from exhaust duct data. Consistent estimates of $S_{in,le}$ and $S_{S,le}$ require detailed recording of trajectories of all fluid elements of contaminants. In this study two experimental methods for estimation of η^{d}_{le} are given: a numerical method and a field method. Those methods are applied to a case of a passive contaminant source located 0.2 m below a square exhaust opening (0.1 x 0.1 m). To demonstrate the influence of the size of the control box on direct capture efficiency, two different sizes are considered: cubes with edges of 0.25 m (box A) and 0.40 m (box B), respectively.

Numerical method

The TEACH-code is used for steady state calculation of the 3-D velocity and concentration field under isothermal conditions. The standard two-equation k-ε turbulence model is used (3). A more detailed description is shown by Madsen et al.(4). The model is applied to an actual test room with a local exhaust system (Figure 2). The numerical model is validated in the laboratory using the test room shown in Figure 2. Validation is performed in terms of air velocity field and local mean age of air, and a fair agreement has been obtained (4).

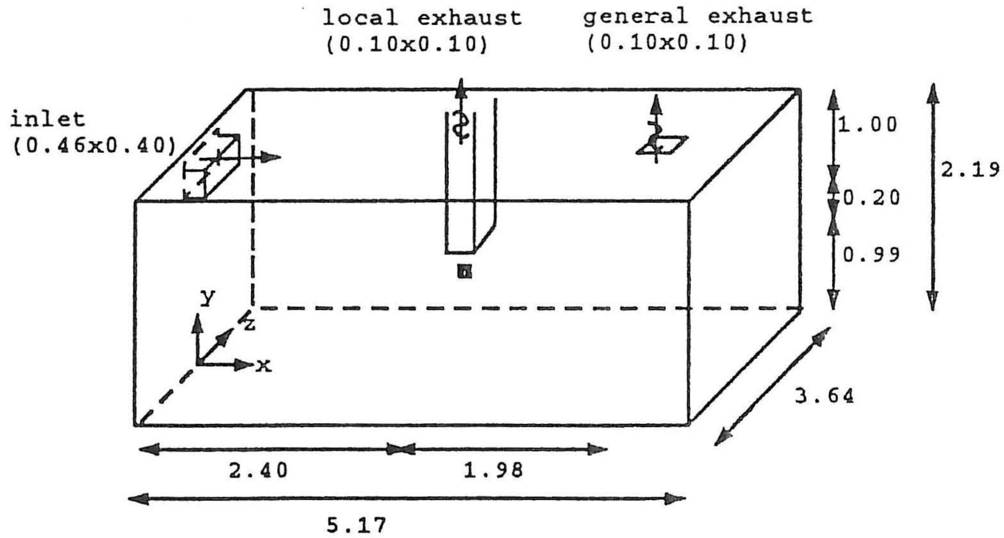

Figure 2. Configuration of the ventilated room.

As an approximative solution for this study the pollutant flow, S_{in}, into the control box is substituted for $S_{in,le}$. The flow S_{in} is computed as the sum of convective flow S^{C}_{in} and of diffusive flow S^{D}_{in}, the latter taking turbulent as well as laminar diffusion into account. Let a surface element have an area of dA. Mean air velocity at the normal of an element is v_n, contaminant concentration is c and gradient of contaminant concentration at the normal of the element is dc/dx. Let D denote the diffusion conductance. The contaminant flow into the control box is computed as

$$S_{in} = S_{in}^{C} + S_{in}^{D} = \Sigma \left(\rho \; v_n \; c + D \frac{dc}{dx}\right) dA \tag{4}$$

where $v_n = |v_n|$ for air velocity into the box, and $v_n = 0$ for air velocity out of the box
$dc/dx = |dc/dx|$ for diffusion into the box, and $dc/dx = 0$ for diffusion out of the box
ρ = density of contaminant

Let capture efficiency derived from S_{in} be denoted η^1_{le}. From Equations (2c) and (3) it is observed that the following relation applies

$$\eta^1_{le} = \frac{S_{le} - S_{in}}{S} = \eta^d_{le} - \frac{S_{in,out}}{S} \qquad (5)$$

Field method

From an experimental point of view the approach of Equation (3) is far from obvious. For field applications $S_{in,le}$ can be obtained from knowledge of airflow patterns and concentrations of air contaminants at surfaces of the control box. Only part of air entering the control box leaves the box by the local exhaust. Let $<c_b>$ be the average contaminant concentration (background) of this airflow. Then $S_{in,le}$ is given as $<c_b> \times q_{le}$. Let the derived direct capture efficiency be denoted η^2_{le}:

$$\eta^2_{le} = \frac{(c_{le} - <c_b>) \times q_{le}}{S} \qquad (6)$$

No strategy seems available when representative locations for measuring concentrations are to be selected for the estimation of $<c_b>$. In this study two strategies are applied: (a) sampling at centres of surfaces of a cube without taking knowledge of airflow patterns into account (η_{le}^{2a}), and (b) sampling at centres of surfaces of a cube taking knowledge of airflow patterns into account (η_{le}^{2b}).

For a given surface, No. *i*, the concentration obtained is c_{bi}. To estimate η_{le}^{2a} (no knowledge of airflow patterns) $<c_b>$ is computed as the mean value of data obtained. To estimate η_{le}^{2b} (knowledge of airflow patterns) $<c_b>$ is computed as an air flow rate weighted mean concentration.

$$<c_b> = \frac{\sum \alpha_i \times c_{b,i}}{\sum \alpha_i} \qquad (7)$$

α_i denotes the fraction of air entering the cube, removed direct by the local exhaust system. In this study α_i is "measured" by releasing a small amount of smoke at location No. *i*. By following the trajectories of the smoke a visual estimate of α_i is conducted. To take into account the fluctuating behaviour of the flow field, an average of ten observations is used. It is recognized that the technique used for estimation of α_i is somewhat subjective and further development is called for in this area. In actual field studies concentrations of true contaminants are measured. In this study, however, contaminant concentrations are computed by the numerical model. $<c_b>$ is obtained from Equation 7.

RESULTS

Estimated α-values and computed concentrations are given in Table 1 for the two box sizes.

Table 1. Estimated α-values and computed concentrations for the two box sizes.

Surface No. (i)	Box A (0.25 m)			Box B (0.40 m)		
	α_i	$c_{b,i}$	$\alpha_i x c_{b,i}$	α_i	$c_{b,i}$	$\alpha_i x c_{b,i}$
1 (west)	0.76 ± 0.35*	76.4**	58	0.80 ± 0.31	20.5	16
2 (east)	0.71 ± 0.45	32.0	23	0.47 ± 0.46	5.96	2.8
3 (bottom)	0.94 ± 0.10	36.1	34	0.87 ± 0.19	0.45	0.39
4 (top)***	0.84 ± 0.15	9.95	8.4	0.46 ± 0.17	13.3	6.1
5 (left)	1.00 ± 0.00	59.7	60	0.64 ± 0.33	11.7	7.5
6 (right)	0.87 ± 0.28	59.7	52	0.79 ± 0.25	11.7	9.2
Sum	5.12		235	4.03		42

* Mean ± standard deviation (N=10)
** Concentrations given as percentage of local exhaust air concentration.
*** The mean values of four observations, obtained at the diagonals 0.07 m from the corners of the exhaust duct, are used because the centre of the surface is occupied by the exhaust duct.

Estimated local exhaust capture efficiencies, $\eta^{tot}_{le}, \eta^{1}_{le}, \eta^{2a}_{le}, \eta^{2b}_{le}$ are given in Table 2. η^{2a}_{le} is computed without information on the flow field at the boundaries of the control box.

Table 2. Estimated local exhaust capture efficiencies.

Box size	η^{tot}_{le}	η^{1}_{le}	η^{2a}_{le}	η^{2b}_{le}
A (0.25 m)	99.6	54.5	54.2	54.0
B (0.40 m)	99.6	91.6	89.0	89.1

DISCUSSION

Direct capture efficiency is considered to be the most useful parameter of a local exhaust ventilation system. However, for application in general no consistent approach for estimation of this parameter seems available. In this study fundamental concepts are introduced and different approaches for estimation of direct capture efficiency are applied.

η^{1}_{le}, computed by the numerical model, is an underestimate of the true capture efficiency. The total capture efficiency, η_{le}^{tot}, is an overestimate. As observed from Table 2 and Figure 1, capture efficiency, except total capture efficiency, depends on size and location of the selected control box. η_{le}^{d} will be close to, but above, zero if the control box diminishes to a narrow column between the contaminant source and the exhaust opening. As box size increases, direct capture efficiency approaches total capture efficiency. Up to moderate box sizes, Madsen et al.(4) observed a positive correlation for η_{le}^{1}. Even for large boxes η_{le}^{1} does not approach η_{le}^{tot}. This result indicates that further development of the numerical method is needed.

It is common practice, (5) and (6), to estimate capture efficiency from data obtained by sampling from locations in a grid (η_{le}^{2}). However, no sampling strategy is described. In this study two different strategies are applied: (a) sampling at centres of surfaces of a cube without taking knowledge of airflow patterns into account (η_{le}^{2a}), and (b) sampling at centres of surfaces of a cube taking knowledge of airflow patterns into account (η_{le}^{2b}). As observed from Table 2, η_{le}^{2a} is at a level comparable to η_{le}^{2b}. This outcome is to be considered as a coincidence, due to inconsistent data, e.g. as observed in Table 1 at surface No. 1 (box B). A high concentration at the surface indicates a flow of contaminants from the source out of the box. However, a high value of α_i indicates a contaminant transport into the box.

It is emphasized that as the number of sampling points increases and information on air movements at the boundary of the control box is improved, η_{le}^{2b} tends to approach the true value of capture efficiency, η_{le}^{d}. Therefore it is unexpected that $\eta_{le}^{1} > \eta_{le}^{2b}$ (Table 2) as η_{le}^{1} is an underestimate of η_{le}^{d}. The sampling strategies and experimental methods applied in this study are therefore considered insufficient, and further development is needed.

For field application, the following approach for estimation of local exhaust direct capture efficiency is recommended:

- Control box definition: Only areas where contaminants are acceptable are included in the box.

- Sampling strategy: Sampling locations are equally distributed over the faces of the control box. To check that $\eta_{le}^{2} \leq \eta_{le}^{tot}$ sampling at the exhaust duct is included.

- Estimate direct capture efficiency from Equations 6 and 7.

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